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(54) Method of characterizing bistable semiconductor lasers.

(57) The characteristic parameters of a semiconductor laser (1) acting as an amplifier and brought to bistable operating conditions are determined. To this aim the output power (I2) of laser (1) is measured as a function of the power (I1) of an amplitude-modulated optical input signal to determine the laser hysteresis loop; the switching points (P1, P2) between the two stable states of the laser (1) are identified, the input and output power values [I2(P1), I1(P1), I2(P2), I1(P2)] relevant to such points are memorized, and at least the value of the non-linear refractive index coefficient (n_2) of the material used to fabricate the laser (1) is determined starting from the power values relevant to at least one of said points (P1, P2). By exploiting the power values relevant to both switching points (P1, P2) also the amplification factor (A), the finesse parameter (F) of the passive cavity of the laser (1) and the wavelength difference (λ_1-λ_2) between the laser under test (1) and a second laser (3) generating the optical signal causing the laser under test (1) to operate under bistable conditions are measured.

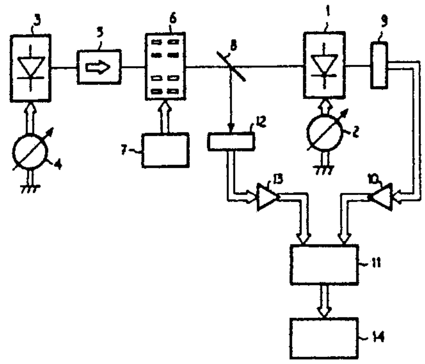

FIG. 1

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Method of Characterizing Bistable Semiconductor Lasers

Description

The present invention refers to semiconductor lasers, and more particularly it concerns a method of characterizing bistable semiconductor lasers.

Bistability is a well known phenomenon, and the bistable behaviour of a number of magnetic materials has been long since exploited in electronics in order to manufacture logic devices, in particular memory devices. The phenomenon is characterized by the existance of two values of an output quantity in correspondence with a same value of an input variable, the attainment of either output value depending on the direction the input value is made to vary.

More recently the same phenomenon has been observed in optical devices (interferometers) made of materials with non-linear properties, i.e., materials in which certain intrinsic parameters (such as refractive index and absorption constant) depend on the input power. More particularly, the refractive index of said devices can be expressed as the sum of a constant term and of a term depending on the power I of the signal sent to the device, according to the relation $n = n_0 + n_2.I$
where n_0 is the linear refractive index (which is constant), while n_2 is the so-called non-linear refractive index coefficient.

Owing to the present interest for optical communication systems, which allow much higher processing speeds than electronic components, it has been proposed to exploit optical bistability to implement optical logic circuits capable of replacing as much as possible the electronic components in said systems. Optical memory devices to be used e.g. in optical switching and processing have been widely described in the literature, said devices using semiconductor lasers (or laser diodes), excited by optical or electrical pulses and made to operate near the stimulated emission threshold. Under said conditions in fact the laser operates as an amplifier and presents an optical power threshold, for switching from the spontaneous emission condition to the stimulated emission condition, different from the threshold which restores the device to the spontaneous emission condition. The existence of two switching thresholds gives rise to the bistable behaviour of the device.

For a correct use of a laser under the conditions above, its characterization from bistability standpoint will be also necessary, and more particularly, the non-linear refractive index coefficient ought to be determined. Various methods are known for measuring such a coefficient in the non-linear material by which the device will be made. The simplest method is based on interferometric techniques and is described e.g. by D. Milam and M.J. Weber in the paper entitled "Measurement of non-linear refractive index coefficient using time-resolved interferometry: Applications to optical materials for high-power neodymium lasers", Journal of Applied Physics, Vol.47, 1976, pages 2497 and ff.

According to such a method a sample of the material is introduced into an interferometer branch, a variable-intensity light beam is launched into the sample, so as to cause a refractive index variation, and the interference fringe shifts due to such index variations are measured: n_2 is obtained from such shifts. A correct evaluation of the positions of the visibility maxima and minima requires an accurate digital processing of the experimental data to eliminate the noise present in the measurement.

No technique has been till now suggested for measuring n_2 directly in a device in operating conditions. This determination can be more significant than that on the material, since it is to be presumed that also the non-linear refractive index coefficient, like the linear refractive index, is modified when introducing the material into a device.

The invention provides a method for measuring the characteristic parameters of a semiconductor laser, which is biased by a current causing it to act as an amplifier and is brought to bistable operating conditions by an optical pump signal, obtained by amplitude modulating a light beam emitted by a second semiconductor laser operating at a wavelength slightly exceeding that of the laser under test, wherein: the laser output power is measured as a function of the input power to determine the hysteresis loop of said output power; the switching points between the two laser stable states are identified by using the power values measured; the output and input power values relevant to such points are memorized and the non-linear coefficient of the refractive index of the non-linear material used for the laser fabrication is obtained from the output and input power values relevant to at least one of such points.

According to another characteristic of the method, also the amplification factor, the finesse parameter of the laser cavity and the wavelength difference between the laser under test and said second laser are determined starting from the power values relevant to both switching points

According to a further characteristic of the method, the laser reflected power is measured as a function of the input power to determine also the hysteresis loop of said reflected power, and the single-pass gain of the laser is determined starting from the values of the output power, the reflected power and the input power.

The method can be performed by using the same equipments as used in the applications of a bistable laser (e.g. in signal regeneration and/or amplification systems). This is an advantage over the known method, which theoretically could be employed for measuring coefficient n_2 not only in the material but also in a device and yet in this case would be performed by using other equipments than those used in the practical applications of the bistable laser.

Besides, not only does the method provided by the invention permit non-linear refractive index coefficient measurement, but also a complete optical characterization of the laser.

For a better understanding, reference is made to the annexed drawings, in which:

- Fig. 1 is a schematic representation of the apparatus used for performing the method;
- Fig. 2 represents the transmission hysteresis loop of the laser;
- Fig. 3 is a diagram of the laser transmittivity versus the intensity of the beam outgoing from the laser itself;
- Fig. 4 is a schematic representation of a variant embodiment of the apparatus;

and

- Fig. 5 represents the reflection hysteresis loop.

In Fig. 1, where double lines represent electrical connections and single lines optical signal paths, reference 1 denotes the bistable semiconductor laser under test, which is a conventional single-longitudinal mode laser, connected to a generator 2 of a highly stable bias current, such as to make laser 1 operate near its threshold and act as an amplifier. As known, bistable operation of a semiconductor laser is obtained by launching into said laser an optical pump signal, having a wavelength slightly different from that emitted by laser 1. That pump signal is generated by a second semiconductor laser 3, analogous to laser 1, connected to a respective bias current generator 4, this too highly stable. For simplicity of drawing the systems for stabilizing the laser working temperature are not shown, since their function is of no interest for the invention.

According to the present invention, when carried out by the apparatus shown in Fig. 1, characterization of laser 1 exploits the laser hysteresis loop expressed by the intensity of the light outgoing from the laser as a function of the input light intensity. To build up the hysteresis loop, the beam generated by laser 3 is sent via an insulator 5 to an acousto-optical device 6, fed by an amplitude-modulated carrier, more particularly a carrier modulated by a sinusoidal signal. The aim of insulator 5 is that of preventing back-reflections which could annoy the measurement. Reference 7 schematises the whole of the devices generating the modulated carrier. The beam outgoing from acousto-optical device 6 (e.g. the beam deflected into the first Bragg diffracted order), which has a sinusoidally varying intensity, is sent to a beam splitter 8 forming a transmitted partial beam and a reflected partial beam. The transmitted partial beam is sent to laser 1 under test, it is optically amplified by laser 1 and then is collected by a photodetector 9 whose output is connected, through an amplifier 10, to the y input of a memory oscilloscope 11 operated in x-y mode. The partial beam reflected by beam-splitter 8 is collected by a second photodetector 12 whose output is connected through an amplifier 13to the x imput of oscilloscope 11. For simplicity sake the various optical systems collimating, focusing etc. the light beams have not been shown as they are of no interest to the present invention.

Oscilloscope 11 stores the amplitude values of the signal outgoing from photodetector 9 (which are proportional to the values of intensity I2 of the beam outgoing from laser 1) as a function of the amplitude of the signal outgoing from photodetector 12 (which amplitude is proportional to intensity I1 of the beam injected into the laser itself). The transmission hysteresis loop of laser 1 is built up in this way. A data processing device 14, connected to oscilloscope 11, identifies switching points P1, P2 between the two states and, starting from values I2(P1), I1(P1), I2(P2), I1(P2) of I2 and I1 at such points, it calculates either the non-linear refractive index coefficient alone or said coefficient and other parameters characterizing the laser, more particularly the amplification factor, the finesse parameter and the wavelength difference between the emitted signal and the pump signal.

Switching points P1, P2 can be identified either by obtaining the laser transmittivity from values I2, I1, or directly from the hysteresis loop.

Laser transmittivity can also be exploited in a check phase, wherein at least the correctness of value n_2 can be verified starting from the transmittivity maximum.

Fig. 2 shows the hysteresis loop of I2 versus I1, and Fig. 3 transmittivity T versus I2. Straight lines represent T when T is expressed by ratio I2/I1; the curve represents on the contrary the function

$$T = \frac{A}{1+AF\sin^2\left[2\pi\left(\frac{\lambda_2-\lambda_1}{\lambda_1\lambda_2}\cdot L\cdot n_0+\frac{L}{\lambda_1}n_2 I_2\right)\right]} \qquad (1)$$

which links T to the parameters of the laser, considered as a non-linear Fabry-Perot interferometer whose cavity is filled with a material having refractive index $n = n_0 + n_2.I2$. The relation is valid in the small optical signal approximation (far from gain saturation, as it occurs when using laser 1 as an amplifier) and assuming for simplicity a plane wave propagation. In such relation: I2, I1, n_0, n_2 have the already-examined meaning; λ_1, λ_2 are the wavelengths of lasers 3 and 1, respectively; A is the amplification factor of laser 1 under resonance conditions; F is the finesse parameter of the passive cavity of length L and resonance wavelength λ_2. Only the first peak of the curve representing relation (1) has been considered, namely the peak for which the argument of the sinus function at the denominator is 0. The operating condition in which such peak is exploited is easily obtained by a suitable choice of the wavelength difference between lasers 1 and 3, more particularly by exploiting the resonance wavelength λ_2 of laser 1 closest to λ_1: in an exemplary embodiment, wavelength λ_1 and λ_2 were 832.1 nm and 831.9 nm, respectively. The dashed area in Fig. 3 corresponds to the hysteresis loop of Fig. 2.

The theoretical principles on which the method of the invention is based will now be disclosed in more detail, with reference also to the diagrams of Figs. 2 and 3.

As mentioned, in order to obtain n_2, switching points P1, P2 between the two stable states are to be identified and this can be made by either exploiting transmittivity T or directly starting from the hysteresis loop.

The method which exploits transmittivity is based on the consideration that such points are those in which, as I2 varies, the straight lines and the curve in Fig. 3 are mutually tangent. Such points can be determined by calculating the first derivatives, with respect to I2, of the two expressions of T and by equalling such derivatives. Indicating for the sake of simplicity by ϕ the argument of the function $\sin^2$ at the denominator of (1), relation

$$\frac{1}{I1(Pi)} = \frac{2n_2\cdot L\cdot A\cdot F\cdot \sin\phi\cos\phi}{\lambda_1\cdot(1+AF\sin^2\phi)} \qquad (2)$$

is obtained for the generic switching point Pi (with i = 1, 2). Let us suppose that only coefficient n_2 of a laser of which A, F, $\lambda_2 - \lambda_1$ are known is to be measured: by replacement $\sin\phi$ by its value expressed as a function of I1(Pi), I2(Pi) (which value can be extracted from (1)) and expressing $\cos\phi$ as a function of $\sin\phi$, relation (2) immediately provides n_2, which is the only unknown parameter and is given by relation

$$n_2 = \frac{I_1\lambda_1}{4\pi\ L\ I_2\ \sqrt{I_1-I_2/A}\ \sqrt{FI_2-I_1+I_2/A}} \qquad (3)$$

It is clear that the identification of a single switching point Pi is sufficient to determine n_2. Yet n_2 can be advantageously obtained also from the data relevant to the other switching point, and the average between the two values thus computed can be taken as actual value of n_2.

Identification of both switching points is on the contrary necessary to determine also A, F and $\lambda_2 - \lambda_1$, besides n_2. By introducing into relations (1) and (2) the power values relevant to points P1 and P2, a 4-equation system in the four above-mentioned unknown quantities is obtained, which system can be solved by processing device 14.

The method of identifying points P1, P2 directly from the hysteresis loop is based on the observation that such a loop presents two straight-line segments indicating the transitions from one state to the other: the starting points of such straight-line segments (with reference to the direction of variation of I1) are the two switching points. Processing device 14 can easily obtain, from the measured values of I2 and I1, the straight lines better approximating such portions and recognize the switching points as the points wherein the straight lines and the curve are no longer coincident.

Advantageously, the method of the invention provides, besides the characterization step, a step in which there is checked the correctness of the value of n2 determined by either method described above, and possibly also of the value of A. For such check, the values of T are determined by exploiting the values of I1 and I2 already used to obtain the hysteresis loop, and the values of I2 and I1 where transmittivity is maximum are determined. Taking into account relation (1) and by indicating again by ϕ the argument of function $\sin^2$, it is evident that such maximum value is reached when $\phi = 0$ (in the hypothesis that wavelength difference $\lambda_2 - \lambda_1$ is chosen so as to exploit the resonance peak of laser 1 closest to λ_1): by substituting in the expression of ϕ the value of I2 for which such maximum occurs, the value of n2 is obtained, expressed by

$$n_2 = \frac{n_0 (\lambda_1 - \lambda_2)}{\lambda_2 \cdot I_2} \quad (4)$$

In addition, since the maximum value of T is A, as it can be immediately deduced from (1), there is also a check on the measurement of the amplification factor, if such a measurement is made.

The apparatus shown in Fig. 1 can be modified as shown in Fig. 4 so as to measure the power reflected by laser 1 in order to allow determination also of the single-pass gain G of the laser. The knowledge of G allows also a different determination of amplification factor A which, in the same conditions of validity of relation (1), is expressed by

$A = (1 - r)^2G/(1 - rG)^2$ (5)

where r is the reflectivity of the laser facets. Thus, a further check of the measurement based on the transmission hysteresis loop is possible.

As shown in Fig. 4, the output signal of amplifier 13 (which is proportional to laser input power I1) is sent also to input x of a second memory oscilloscope 15 operated in x-y mode. The y input of oscilloscope 15 is fed, via an amplifier 16, with the output signal of a further photodetector 17 which receives, via beam splitter 8, a light signal consisting of the pump signal fraction reflected by the input face of laser 1. Like oscilloscope 11, oscilloscope 15 stores the amplitude values of the output signal of detector 17, proportional to intensity I3 of the beam reflected by the laser 1, as intensity I1 of the pump signal varies. Thus the reflection hysteresis loop is built, as shown in Fig. 5.

Processing device 14, connected also to the output of oscilloscope 15, determines the angular coefficients of the straight lines which approximate the transmission and reflection hysteresis loops in the switching regions, and calculates single-pass gain G starting from such angular coefficients.

The theoretical considerations on which the invention is based for the determination of G are as follows. Input power I1, transmitted power I2 and reflected power I3 are mutually linked by relation

$I3 = I1 + BI2$

which, denoting by R the laser reflectivity I3/I1, corresponds to relation $R = 1 + BT$ where B, under the same conditions of validity of (1), is expressed by

$B = (rG^2 - 1)/G \bullet (1 - r)$ (6).

According to the invention, in order to determine G, the value of B is calculated starting from relation

$B = (I3 - I1)/I2$ (7).

Now, B is a constant quantity, as r is a constant constructional parameter and G is constant under the conditions where (1) and (6) apply. Therefore, the first derivative of B with respect to I1 will be 0 whatever the point where it is calculated, and in particular in the straight-line switching regions of the hysteresis loops including switching points P1, P2. By equalling the derivative to 0, the following relations are obtained:

$I2(Pi).[b(Pi) - 1] - a(Pi).[I3(Pi) - I1(Pi)] = 0$ $(i = 1, 2)$ (8)

where $a(Pi) = (dI2/dI1)_{Pi} = tg\theta_T(Pi)$ and $b(Pi) = (dI3/dI1)_{Pi} = tg\theta_R(Pi)$ are the angular coefficients of the straight-line segments of the transmission and reflection hysteresis loops, respectively. From (7) and (8) two values of B are obtained, according to relations

$B(Pi) = [b(Pi) - 1]/a(Pi)$ (9)

Generally, said values do not coincide, because the straight-line portions of each hysteresis loop are not exactly parallel. Thus, it will be convenient to calculate G from a weighted average value Bm of B, expressed by relation

$Bm = [a(P1).B(P1) + a(P2).B(P2))/[a(P1) + a(P2)]$ (10)

which is obtained from relation (9) by replacing a and b by a respective mean value. Then an average value Gm

$Gm = [(1 - r)Bm + \sqrt{(1 - r)^2Bm^2 + 4r}]/2r$ (11)

of a single-pass gain can be obtained by introducing (10) into (6) and solving with respect to G.

It is to be pointed out that facet reflectivity r, if it is not known in advance, may be determined in a calibration phase of the equipment by measuring the power reflected by laser 1 in idle conditions.

Value Gm may subsequently be employed to calculate A according to relation (5).

Claims

1. A method of measuring the characteristic parameters of a semiconductor laser (1), which is biased by a current making it act as an amplifier and is brough to bistable operating conditions by an optical pump signal, obtained by amplitude modulating a light beam emitted by a second semiconductor laser (3) operating at a wavelength (λ_1) slightly exceeding that (λ_2) of the laser under test (1), characterized in that: the output power (I2) is measured as a function of the input power (I1) to determine the hysteresis loop of said output power; the switching points (P1, P2) between the two stable states of the laser under test (1) are identified by using the power values measured; under output and intput power values [I2(P1)], I1(P1), I2-(P2), I1(P2)] relevant to such points are memorized and the values of the non-linear coefficient (n_2) of the refractive index of the non-linear material used for manufacturing the laser under test (1) is derived from the output and input power values relevant to at least one of such points.

2. A method as claimed in claim 1, characterized in that, in order to identify the switching points, the transmittivity (T) of the laser (1) is obtained from the input and output power values (I1, I2), and the values of said transmittivity (T), expressed as the ratio between output and input powers (I2, I1), are compared with the values of same when expressed as a function of the laser parameters (A, F, n_2, $\lambda_2 - \lambda_1$), the switching points being the points for which the first derivative, calculated with respect to the laser output power (I2), of transmittivity (T) expressed as ratio between output and input powers and as a function of the laser parameters are equal.

3. A method as claimed in claim 1, characterized in that the input and the output power values where the hysteresis loop has no longer a rectilinear trend are determined to identify the switching points.

4. A method as claimed in any of claims 1 to 3, characterized in that, by exploiting the input and output power values relevant to both switching points (P1, P2), also the amplification factor (A), the finesse parameter (F) of the laser (1) and the wavelength difference ($\lambda_2 - \lambda_1$) between the laser under test (1) and said second laser (3) are measured.

5. A method as claimed in any preceding claim, characterized in that it comprises a checking step for checking the correctness of the measurement of the non-linear refractive index coefficient (n_2), in which step the transmittivity (T) of the laser under test (1) is measured as a function of the output power (I2), the maximum of such transmittivity is detected and the non-linear coefficient of the refractive index is obtained from the output power value where said maximum occurs.

6. A method as claimed in any preceding claim, characterized in that the power (I3) reflected by the laser (1) under test is measured as a function of the input power (I1) to determine the hysteresis loop of said reflected power, and the single-pass gain (G) of said laser under test (1) is determined starting from the values of the reflected power (I3), the output power (I2) and the input power (I1).

7. A method as claimed in claim 6, characterized in that the measurement of the single-pass gain (G) comprises the steps of: determining the angular coefficients [a(P1), b(P1), a(P2), b(P2)] of the straight lines which, in said hysteresis loops, approximate the transition regions between the two stable state of the laser under test (1); calculating, starting from said angular coefficients (a, b) the value of a parameter (B) which links the laser reflectivity (R) and transmittivity (T) and is a function of said gain (G); and computing the gain (G) from the value of said parameter (B).

8. A method as claimed in claim 7, characterized in that an average value (Gm) of the gain is determined, starting from a weighted average value (Bm) of said parameter obtained from an average value of the angular coefficients of the two straight lines that, in each of said hysteresis loops, approximate the two switching regions.

9. A method as claimed in any of claims 6 to 8 if related to claim 4, characterized in that the value of the amplification factor (A) is calculated starting from the single-pass gain (G), for checking the measurement based on the hysteresis loop of the output power.

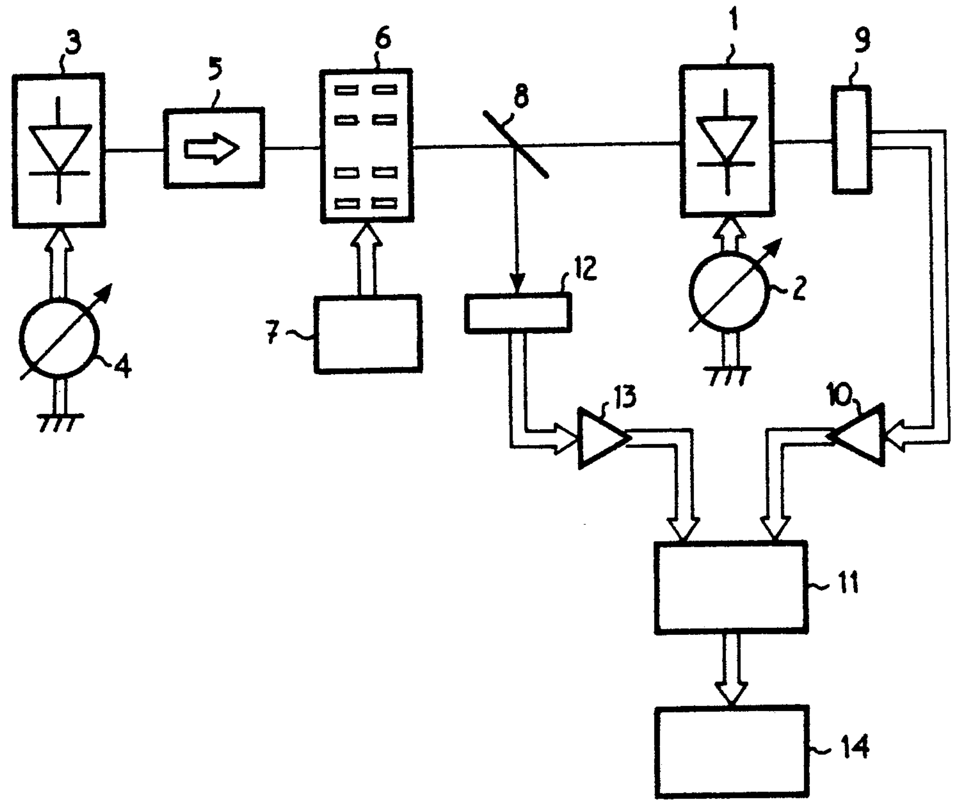

FIG. 1

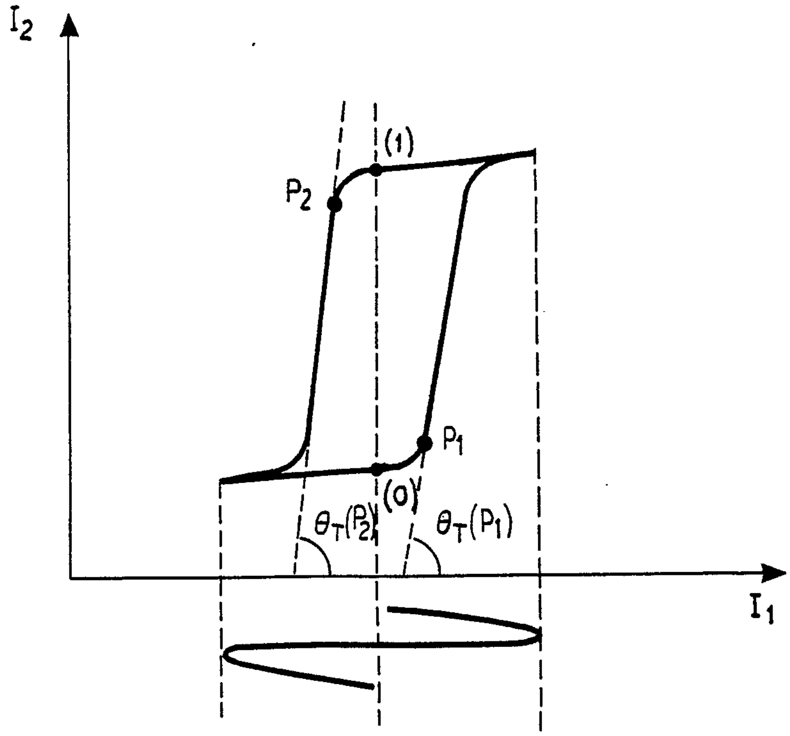

FIG. 2

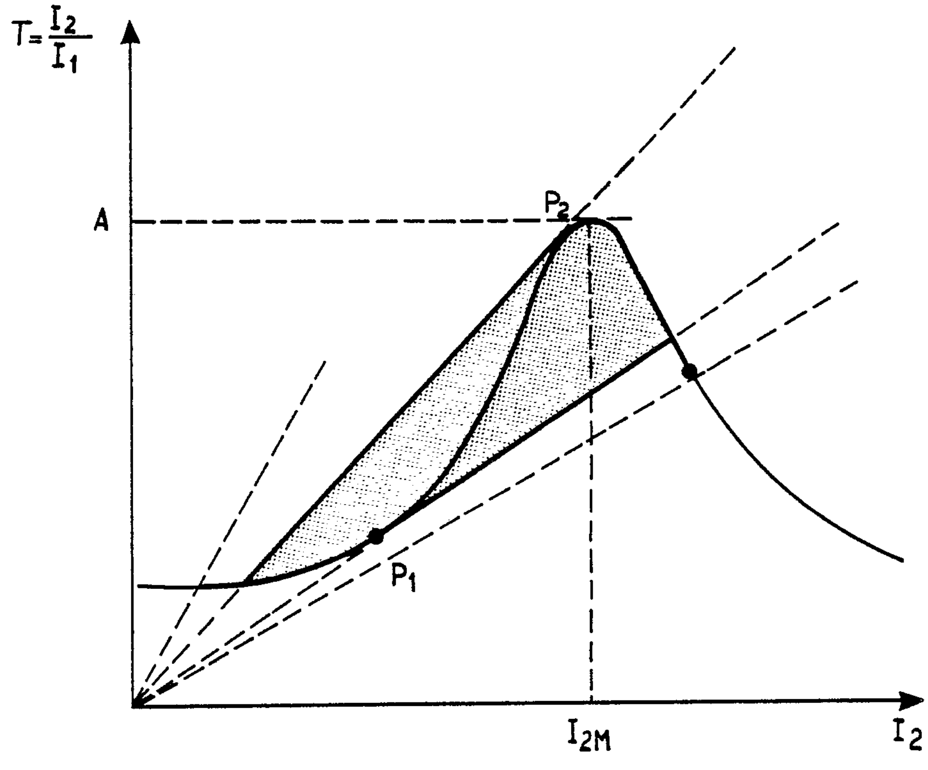

FIG. 3

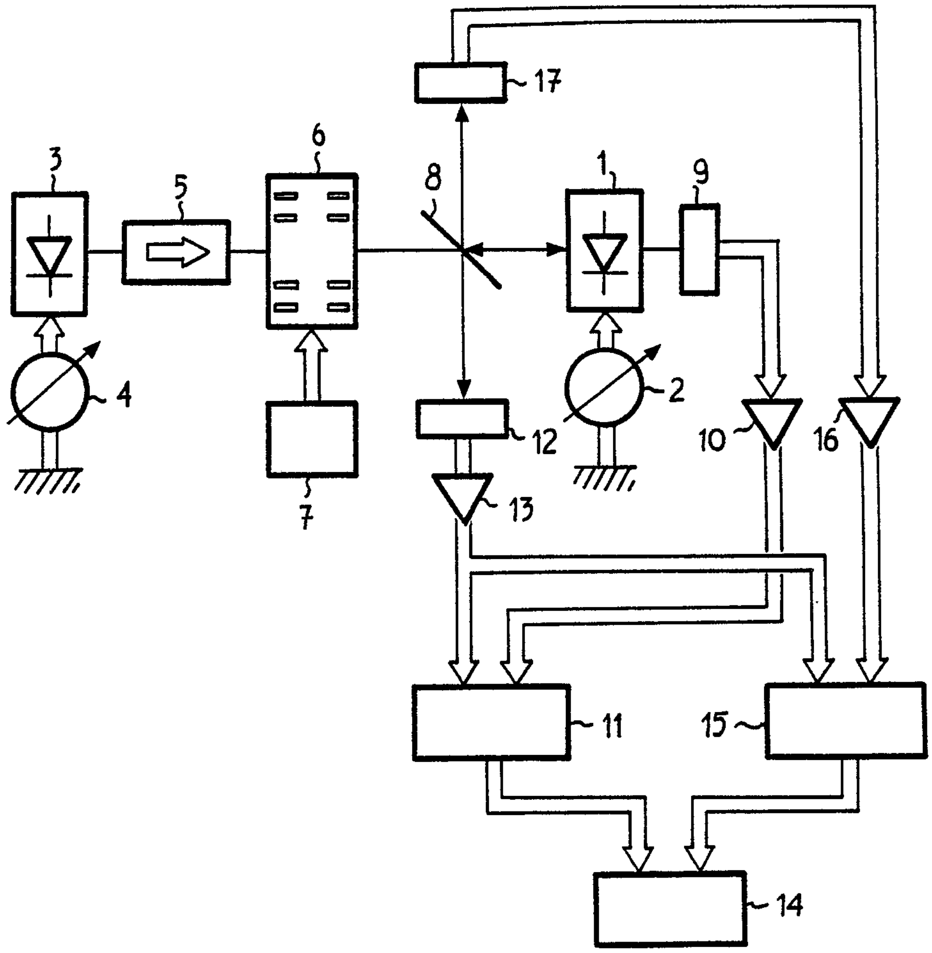

FIG. 4

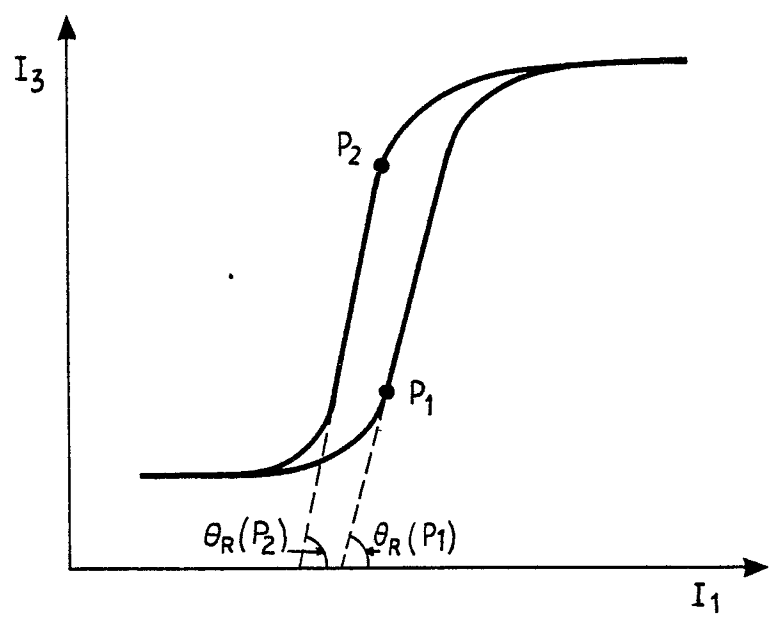

FIG. 5